Application of Quantum-Classical Genetic Algorithms to Network Signal Setting Design

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***Abstract*—The signal setting design in urban networks leads to complex optimization challenges, especially in presence of connected and electric vehicles. To address these problems, meta-heuristic algorithms are commonly employed, especially when deterministic exact solutions cannot be found efficiently. This study demonstrates the effectiveness of a hybrid quantum-classical genetic algorithm in solving both a mono-objective and a multi-objective optimization problem where the objective functions to minimize are the total deterministic delay (TDD) and the energy consumption (EC) of elecric vehicles in a signalized network. The results highlight the strengths of this approach compared to purely classical methods, suggesting its applicability to more intricate real-world scenarios.**

***Index Terms*—genetic algorithms, multi-objective optimization, quantum computing, signal setting, connected vehicles, energy consumption, electric vehicles**

I. INTRODUCTION

One of the main challenges in a smart city scenario lies in the development of solutions that integrate drivers, technologies, and infrastructures to enhance performance levels and energy efficiency of fully connected transportation systems. Intelligent and dynamic control of traffic lights is among the primary approaches used to enhance the efficiency of signalized road junction networks. Implementing this strategy translates in solving a — typically multi-objective — optimization problem named *Network Signal Setting Design (NSSD)*, which often involves a large number of decision variables and constraints. Meta-heuristic algorithms, such as evolutionary algorithms (EAs), are usually adopted for this purpose because they allow to approximate the optimal solution with a near-optimal one with much less computational effort. Genetic Algorithms (GAs) are one of the most common effective and versatile meta-heuristics. GAs are frequently employed in NSSD wokflows, where it is important to use algorithms that guarantee a fast performance and are capable of adapting to an environment which is constantly evolving (such as the traffic conditions in urban networks). Among the latest attempts to boost the performance of GAs, quantum computing (QC) represents one of the most pioneering innovations. QC is a new paradigm of computation where information is processed using quantum computers, whose working is based on controlled manipulation of quantum systems and quantum phenomena (superposition, entanglement and interference). In current so-called *Noisy Intermediate-Scale Quantum* (NISQ) era [3], quantum algorithms have shown potential to integrate with classical algorithms within hybrid quantum-classical frameworks, in order to achieve improved performances. In the context of GAs, this approach leads to innovative encoding schemes and implementations of genetic operators, which have a crucial impact in driving successful evolutionary processes. In this abstract we present the results obtained by applying classical GAs and quantum GAs based on the Quantum Mating Operator (QMO) introduced in [1], which is a quantum implementation of crossover and mutation operations that can be integrated in a classical genetic workflow. The algorithms are evaluated in terms of their performances in solving a NSSD problem where different competing performance indicators of a signalized arterial must be optimized, namely the TDD and the EC of electric vehicles. Our results show that quantum-classical GAs can be a valuable asset for smart cities as they prove to be a suitable approach for this type of optimization problems. Furthermore, we believe that delving into novel and intelligent computational techniques within the field of transport engineering is worth pursuing in future research efforts, so that new hybrid quantum-classical algorithms can be designed and tested in increasingly complex and realistic scenarios.

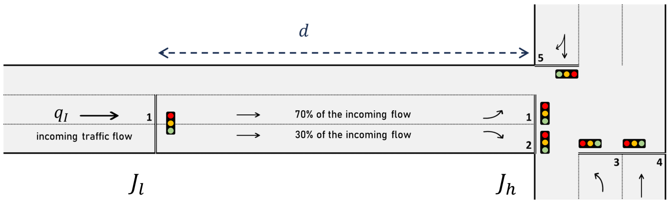

Fig. 1. Arterial layout.

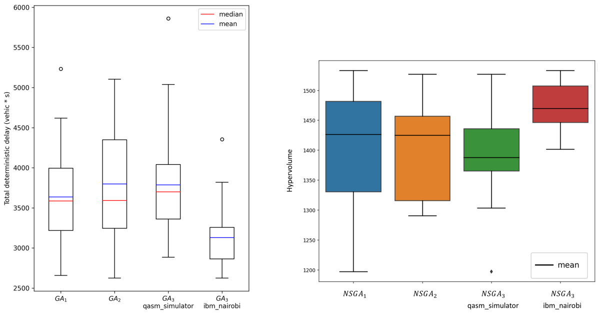

Fig. 2. Left side: box plots showing mean values of mono-objective GA's fitness function (i.e., the TDD) over 30 executions. Right side: box plots showing mean values of Pareto-front-bounded hypervolume values in the two-dimensional objective space over 15 executions.

II. EXPERIMENTS

The NSSD instance chosen for our experiments is set in a network consisting of an arterial joining two signalised junctions: an upstream junction J_l and a downstream junction J_h, shown in Fig. 1. The vehicles' flow is simulated according to Robertson's trafic model, which allows for the calculation of objective function values. We refer to [4] for further details on the arterial characterization and the traffic simulation.

A. *Mono-objective Optimization*

In the first part of the experiment the objective function to minimize is the TDD at junction J_h over a fixed time interval T. The decision variables are time intervals representing stage durations of cyclical green timings and the offset between the upstream and downstream cycles. Different values of decision variables translates into different traffic profiles, which in turn affect the amount of total delay. A hybrid quantum-classical genetic algorithm based on QMO (referred to as GA_3) is compared with two classical GAs (GA_1 and GA_2) equipped with conventional crossover and mutation operators (see [4] for further details). Their performances are evaluated in terms of average TDD values over 30 independent executions. The QMO-based GA is run using IBM Quantum's Qiskit. In particular, both an ideal quantum computer simulator (named *qasm_simulator*) and a real (therefore, prone to noise and decoherence) quantum computer simulator (named *ibm_nairobi*) are used. The results are shown in the box plots on the left side of Fig. 2.

B. *Multi-objective Optimization*

In the second part of the experiment the optimization problem outlined in II-A is turned into a multi-objective problem by adding a second objective function, namely the EC of electric vehicles (whose estimate is discussed in [2]), which competes with TDD. The same approach of II-A is adopted, but the different genetic operators are inserted in the framework of the *Non-Dominated Sorting Genetic Algorithm (NSGA-II)*, one of the most common GAs for multi-objective optimization [6]. The performances are evaluated in terms of average Pareto front hypervolume (i.e., the volume in the objective space bounded by the Pareto front of non-dominated solutions) over 15 independent executions. The results are shown in the box plots on the right side of Fig. 2.

III. RESULTS

In the mono-objective problem there is no remarkable difference among the performances of GA_1 and GA_2. Similarly, in the multi-objective problem, $NSGA_1$ and $NSGA_2$ achieve similar performances in terms of average hypervolume. As regards the QMO-based GAs, i.e., GA_3 and $NSGA_3$, the following behaviour can be observed: if the quantum part of the algorithm is executed on an ideal simulator, no improvement is observed; if, on the other hand, a noisy simulator is employed, the algorithm outperforms all the other ones both in terms of minimized average TDD (or maximized average hypervolume) and reduced variability across iterated runs. On average, the QMO-based GAs run on the noisy quantum simulator are more likely to achieve better optimization performances at fixed number of evaluations, which makes them more suitable than the other tested classical algorithms in terms of future application in real-world traffic optimization. Therefore, we believe our results further encourage the employment of innovative solution strategies involving quantum computing to solve complex problems in the field of transportation systems, especially looking forward to more challenging scenarios involving larger networks, more realistic traffic flow models, and the integration among different control strategies. Lastly, it is worth noting that, in order for our approach to scale to more complex urban settings, quantum hardware will require further improvements in terms of qubit number and quality, gate fidelity, optimization of circuit design and noise mitigation.

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